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Jet Engine Basics Through Thrust Analysis

Rev 0

Abstract

Purpose of the JEBTTA experiment is to introduce various physical mathematical, scientific, and engineering principles associated with gas turbine engine to students. Here, the scientific concepts in physics, thermodynamics, aerodynamics and mathematics are combined with a hands-on experiment to demonstrate gas turbine propulsion system concepts. The JEBTTA experiment is conducted on a small-scale highly instrumented off-the-shelf turbojet engine. The experimental measurements and physical observations are used to confirm the accuracy of the mathematical and engineering models used to design and to build full size gas turbine propulsion systems. The JEBTTA experiment is designed to attach propulsion system hardware to computer simulations and mathematic models often used to explain various aero and thermodynamic concepts.

Introduction

There are four principal aeropropulsion systems: the engine -driven propeller (either a piston or gas turbine engine), the gas turbine (or jet) engine, the ramjet, and the rocket. The gas turbine engine was developed during World War II. Early jet engines only used hot exhaust gas that was passed through a nozzle to produce thrust and is known as the turbo-jet. Most of today's modern passenger and military aircraft are still powered by gas turbine (turbofan and turbojet) engines because they are environmentally clean, extremely reliable, and highly efficient.

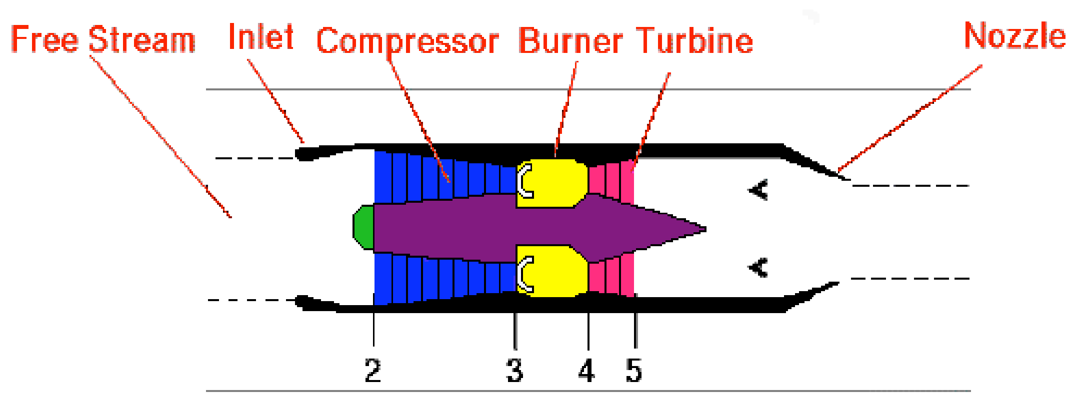


Figure 1 : Typical Turbojet Engine Configuration

Engineers often draw simplified diagrams, called schematics, of an engine to help them understand how the engine works. The schematic is a two-dimensional drawing representing important components of the engine. Propulsion engineers use further shorthand by designating certain locations on the engine schematic with station numbers (as shown). The exit of the inlet, which is the beginning of the compressor, is labeled station "2". The compressor exit and burner entrance is station "3" while the burner exit and turbine entrance is station "4". The exit of the turbine is station "5". There is no nozzle or inlet on the test engine, and therefore no station numbers assigned for them. A numbering system, such as this one, makes technical reports, documents, and conversations much more concise and easier to understand. We will use this numbering system throughout our experiment. Each of these components will be introduced in the following section.

The gas turbine (or, turbojet) engine

Typical jet engine categories are turbojet, turbofan, and turbopropeller. These types of engines have some parts in common. For example, all of these engines have an *inlet* at the front. At the exit of the inlet is the *compressor*. The compressor is connected by a shaft to the *turbine*. The compressor and the turbine are composed of one or many rows of small airfoil shaped blades. The combination of the shaft, compressor, and turbine is called the *turbomachinery*. Between the compressor and the turbine flow path is the *combustor*. This is where the fuel and the air are mixed and burned. The hot exhaust then passes through the turbine and out the *nozzle*. The nozzle is shaped to accelerate the flow, which, in turn, produces thrust.

The *inlet* brings free stream (outside) air into the engine. The inlet sits upstream of the compressor and is important to overall aircraft operation and engine performance. At very low aircraft speeds, or when just sitting on the runway, free stream air is pulled into the engine by the compressor.

The *compressor* increases the static pressure of the incoming air before it enters the combustor. Mechanical work is done on the air by the compressor. At the exit of the compressor, the air is at a much higher pressure than at free stream. The turbine supplies needed mechanical energy to the compressor enabling the compressor to turn. Typically there are two main types of compressors: axial and centrifugal. The flow through an axial compressor travels parallel to the axis of rotation while the flow through a centrifugal compressor is turned perpendicular to the axis of rotation. Our test engine has a centrifugal compressor.

The *power turbine*, located downstream of the burner, extracts energy to turn the compressor, which is linked to the turbine by the central shaft. The turbine takes some energy out of the hot exhaust, but the flow exiting the turbine is at a higher pressure and temperature than the free stream flow. Therefore work is done on the power turbine by the exhaust flow. The turbine, like the compressor, is composed of one row or several rows of airfoil cascades; rotors and stators. Since the turbine is extracting energy from the flow, there is a pressure drop across the turbine. This favorable pressure gradient helps keep the flow attached to the turbine blades, so the pressure drop across a single turbine stage can be much greater than the pressure increase across a corresponding compressor stage. This is the reason why a single turbine stage can be used to drive multiple compressor stages. Turbine blades experience flow temperatures of around 3,000 degrees Fahrenheit since they sit just downstream of the burner. Turbine blades must, therefore, be either made of special metals that can withstand the heat, or they must be actively cooled. (A typical turbine blade is hollow, and cool air, which is bled off the compressor, is pumped through the blade and out through the small holes on the surface to keep the surface cool.)

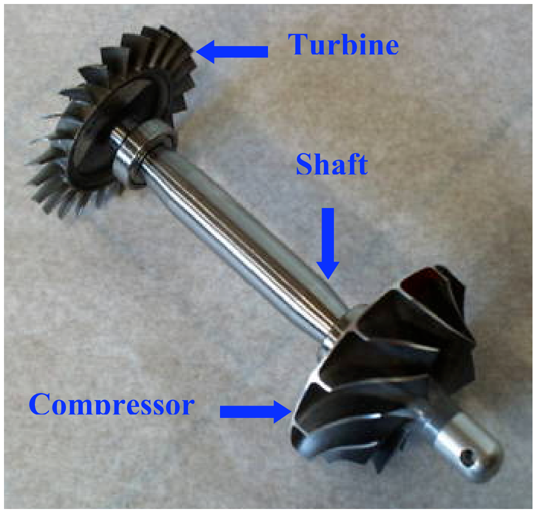


Figure 2 : JetStream 66 Rotating Machinery

The *combustor*, or *burner*, is where the fuel is combined with high-pressure air and burned. The resulting high temperature/high pressure exhaust gas is used to turn the power turbine and to produce thrust. The burner sits between the compressor and the power turbine and is arranged like an annulus, or a doughnut. The central shaft that connects the turbine and compressor passes through the engine's center. Burners are made from materials that can withstand the high temperatures of combustion. There is usually an outer casing and an inner liner. The liner is often perforated to enhance mixing of the fuel and air as well as for cooling the liner.

Figure 3 : JetStream 66: Annular Combustor

The *nozzle* produces thrust while introducing the exhaust gases back to the free stream. The nozzle sits downstream of the power turbine. The flow then passes through the nozzle, which is shaped to accelerate the flow. Nozzles come in a variety of shapes and sizes depending on the mission of the aircraft. Changing the direction of the thrust with the nozzle makes the aircraft much more maneuverable. There is no nozzle on the turbine engine used in our experiment.

Physical Concepts

·Thrust·

There are four forces that act on an aircraft in flight: lift, weight, thrust, and drag. Drag is an aerodynamic force that opposes an aircraft's motion through the air. Airplanes have a propulsion system (an engine) that will generate a mechanical force called thrust to overcome drag. Thrust (F) is the force that moves an aircraft through the air. For jet engines, aircraft thrust is generated through the reaction of accelerating a mass of gas (Newton's Law). Propulsion systems used on aircrafts may vary in arrangement. Thus, the actual mechanical configuration used to produce thrust varies. For a gas turbine engine, the accelerated gas is the jet exhaust and most of the mass of the jet exhaust comes from the surrounding atmosphere. This "action-to-reaction" is explained by Newton's Third Law of motion: for every action there is an equal and opposite reaction. The engine does work on the gas and the accelerated gas creates the equal and opposite reaction. How the aircraft responds depends on the balance of forces on the airplane. Therefore, the amount of thrust generated depends on the mass flow through the engine and the exit velocity of the gas. The change in momentum is equal to the reaction of the force. Mathematically, we define the thrust as a change in momentum.

The thrust to weight ratio is a factor used to characterize aircraft engines. An aircraft with a high thrust to weight ratio has high acceleration (on the basis of Newton's second law of motion). For most flight conditions, an aircraft with a high thrust to weight ratio has high excess thrust values. High excess thrust results in a higher rate of climb and acceleration. If the thrust to weight ratio is greater than one, then the aircraft can accelerate straight up like a rocket.

·Mass flow rate·

Our thrust estimate needs mass flow rate (m). Therefore the amount of mass that passes through the engine must be determined. If fluid is passing through an area (A) at velocity (V), we can define a volume of mass to be swept out in some amount of time (t). So an equation for volume then becomes:

Volume = A * V * t

√ Unit check: (length^2) * (length / time) * time = length^3 = volume.

The mass contained in this volume is simply density (ρ) times the volume. Using the variables from the above equation for volume, the equation for mass becomes:

$$m_{total} = \rho VAt$$

√ Units check: (mass / volume) * volume = mass

Therefore, to determine the mass flow rate, we divide the mass by the time. The time will cancel out of the equation though, giving us the relation:

$$\dot{m} = \rho VA$$

√ Units check: mass/volume * length^2 * (length / time) = mass / time

·Fluid momentum is equal to the mass flow rate times the velocity of the fluid:

$$Momentum = \dot{m}V$$

·How to compute the thrust for a turbojet engine·

Thrust is created due to a change in the momentum of air. Therefore, in a typical propulsion system, thrust can be written as a change in momentum. The thrust (F) produced is equal to the exit mass flow rate (m_e) times the exit velocity (V_e) minus the free stream mass flow rate (m_o) times the free stream velocity (V_o). The equation can be expressed mathematically as:

$$Thrust(Force) = \dot{m}_{exit}V_{exit} - \dot{m}_{in}V_{in}$$

Exit mass flow rate (at station "n") is equal to the free stream mass flow (at station "n") rate times the fuel-to-air ratio (f):

$$\dot{m}_e = (1 + f)\dot{m}$$

An equation for the free stream mass flow rate (at station "n") is as follows:

$$\dot{m}_o = \rho VA$$

·Note that:

ρ= 1.225 kg/m^3 for SSL air
V_n = the velocity at station "n"
A_n = the cross sectional area at station "n"

Velocity (at station "n") can be calculated using the measured T, p, and pt (each at station "n") values in the following equation:

$$Vn = \sqrt{\left[\frac{2a^2}{(\gamma - 1)}\right]\left[\left(\frac{P_t}{P}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

·Note that: $a = \sqrt{\gamma R_{gas} T}$

a_o = the speed of sound

γ = 1.4 for air at STP

R = 287 m^2/s^2/°K for air

$T_{(n)}$ = °R* (5/9) (= °K)

To calculate the fuel to air ratio:

$$f = \frac{m_f}{m_a}$$

·Note that: m_f = fuel mass flow rate

m_a = air mass flow rate

If you would like to learn more about propulsion systems, please visit the NASA Glenn Research Center website at: http://www.lerc.nasa.gov/WWW/K-12/airplane/shortp.html

Pre-Lab

Define the following words:

Velocity-

Momentum-

Newton's Laws:

1.

2.

3.

Conservation of mass:

Conservation of energy:

Conservation of momentum:

Experimental Setup/Parts

Instrumentation List
4 Channel Type K Thermocouple Reader (Omega 1 HH501 DK)
Thermocouples
4 HKQIN-116G-12
4 HKQIN-18G-12

2 HHP-3205 0 to 30 psig (readout to 0.1 psi)
4 KIEl headed pressure probes
1 Custom made Servo Controller with two channels (one proportional, one none)

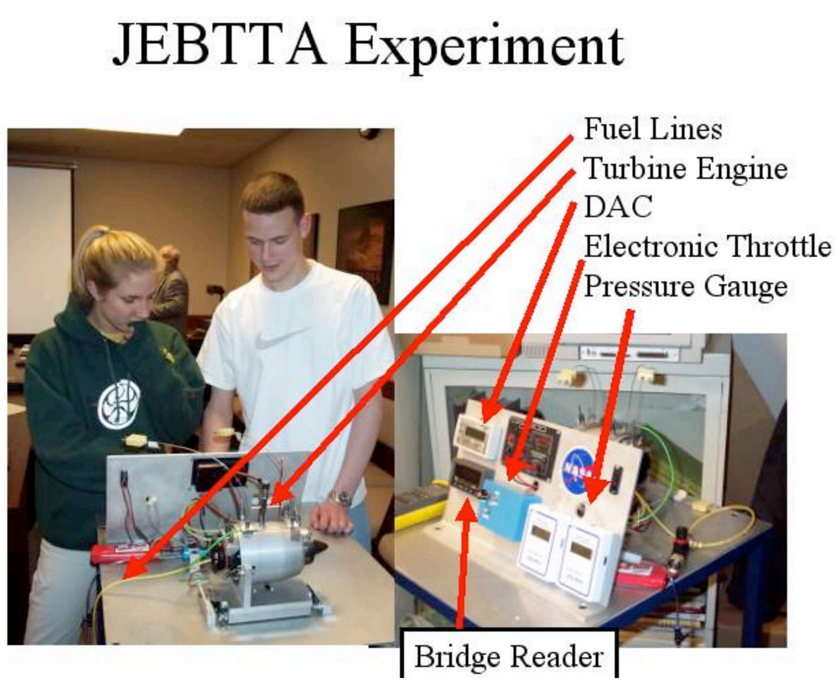


Figure 4 : JEBTTA : Experiment Thrust Stand Layout

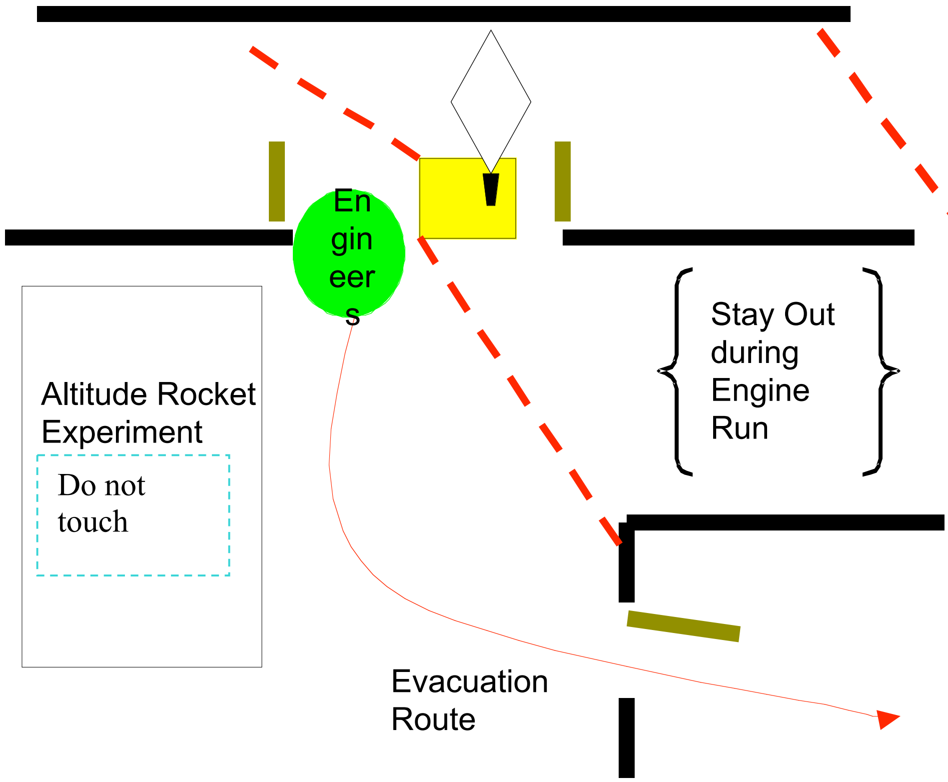
Experimental Procedures

1. Move the JEBTTA rig into place for the test run/face exhaust out of the Cell 11 area.
2. Place all markers around the test area to limit access to the Cell 11 area.
3. Test all electronics for power (replace 9V battery if has not been used in a month)
4. Mix 1 of 50 part of oil to jet-A. Place the fuel tank under the test rig.
5. Place the fire suppression system near the rig.
6. Propane valve has to be closed and connected to the fuel system line.
7. Power on the controller electronics and set the throttle knob to idle. (may need to clear pump by applying power to the pump from external power source.)
8. Power on the DAC and wait for the power on indicator.
9. Check to ensure that the engine rotates freely by blowing into the compressor.
10. Check all instrumentation, fuel systems, and operator readiness.
11. Open the fuel bypass valve (which allows fuel during pump priming to return to the tank) and prime the jet-a fuel system (check the fuel system visually that liquid line is filled)
12. Once the power on switch has been set the DAC reader should indicate GASrun.
13. Record all baseline data.
14. Connect power to the glow plug.
15. Using the start blower, spin up the engine.
16. Eliminate starting air and as rpm falls below 2,000 rpm (DAC displays rpm), **slowly** open the propane valve and wait for the gas turbine to start. Continuous puffing of the air may be necessary to get to the idle temperature.
17. When light up occurs, reinstate starting air (using short bursts) and maintain idle speed.
18. Remove glow power.
19. Once the engine “catches” the propane fire, there should be a slight “hissing” sound and the engine should idle on propane. Adjust the propane valve to achieve an EGT between 275°-400°C (shown on the DAC). A this point the liquid fuel valve should be opened. The fuel pump will start and tone of the gas turbine operation sound will change indicating that the engine is running on liquid fuel. The DAC will read GASidle during this time you should hear the fuel pump running .
20. Close the propane bypass valve. At this point the engine will idle while operational temperature is achieved. The DAC will also read GASaccl.
21. JEBTTA rig is ready for the experiment.
22. Slowly increase throttle stick to achieve various RPM to conduct the JEBTTA experiment.
23. Proceed in observing the measurements of the instrumentation and recording the values of pressure, total pressure, and temperature from each station on the engine, as explained on the following page.
24. All experimental observations shall be recorded as noted earlier.
25. Once the experiment is completed than shutdown the engine and blow cooled air to engine to lower than 96C F EGT before completely shutting down the experiment.

26. At the completion of the experiment. Shut down all sub-systems. Complete a visual inspection and store all of the sub-system.

Safety Guidelines for Gas Turbine Engine Experiment

Engine Experimental layout



Warnings

This miniature turbojet engine is not a TOY! It contains high-speed rotating parts and operates at high temperatures (700F). Anyone not conducting themselves in a professional manner will be asked to leave the test cell area.

Emergency Procedures

- Note in an unlikely event of an emergency, evacuate the cell 11 area through the back of the cell through the mechanic's work area and exit building.

Pre-test cell entry

- Each participant will “sign” an understanding that this engine experiment involves the use of a highly reliable ‘commercial-off-the-shelf ‘ model engine and is reasonably safe to operate but is not risk free. Therefore, they must agree to follow strict experimental protocol prior to being allowed to participate in the JEBTTA experiment.
- A pre-laboratory discussion shall include, theory, experimental procedures and safety rules.
- Adequate hearing protection will be provided and proper use explained.
- Each student will be given an option to decline participation if he or she cannot and/or will not adhere to the experiment guidelines.
- The experiment/demonstration will be coordinated in advance with the facility manager (W. Bartlett 3-5745)
- Security and the facility manager will be notified of any after hours run (B35-4, Cell 11 3-2088).
- No weekend and holiday experiment shall be conducted without permission from the facility management.

During the experiment

- All personal shall stand behind the (JEBTTA) test rig control panel and perform assigned duties as noted in figure 1 and the experimental procedure.
- No one shall touch the engine during or after the experiment. (note the warning above).
- There will be a maximum of 6 persons in the test cell area for the duration of the experiment.
- At least two will be the trained operators listed in the safety permit and will be in charge of the engine monitoring system and the fire suppression system.
- Each of the participants is given one of the following tasks.
    - Monitoring of instrumentation (three people: one for pressure, one for temperature, and one for thrust reading).
    - One person shall in be in charge of recording the data.
    - Visual observation will be made by all (both operator and the students) for any sign of problems prior to the engine start and during the experiment.

Students will not

- Students will **not touch anything** on the engine side of the test stand.
- Students will promptly call out data and record them.
- Students will stand behind the instrument panel and in the safe zone noted in figure 1 at all times.

Qualified operator shall

- Qualified operator will start the engine following the procedure previously developed. The engine shall be put at idle running on jet fuel.

- Qualified operator will monitor the digital engine control (DEC) for exhaust gas temperature and the machine speed at all times.
- The second qualified operator shall keep the fire suppression system within reach.
- Qualified operator shall perform the shutdown process. Hot restart shall not be performed with this engine. The restart can only be initiated if the engine has been cooled down to less than 96 F as noted engine operational notes.
- Qualified operators shall obtain training in fire safety.
- Qualified operator shall a keep a run log to keep track of run time of the engine.

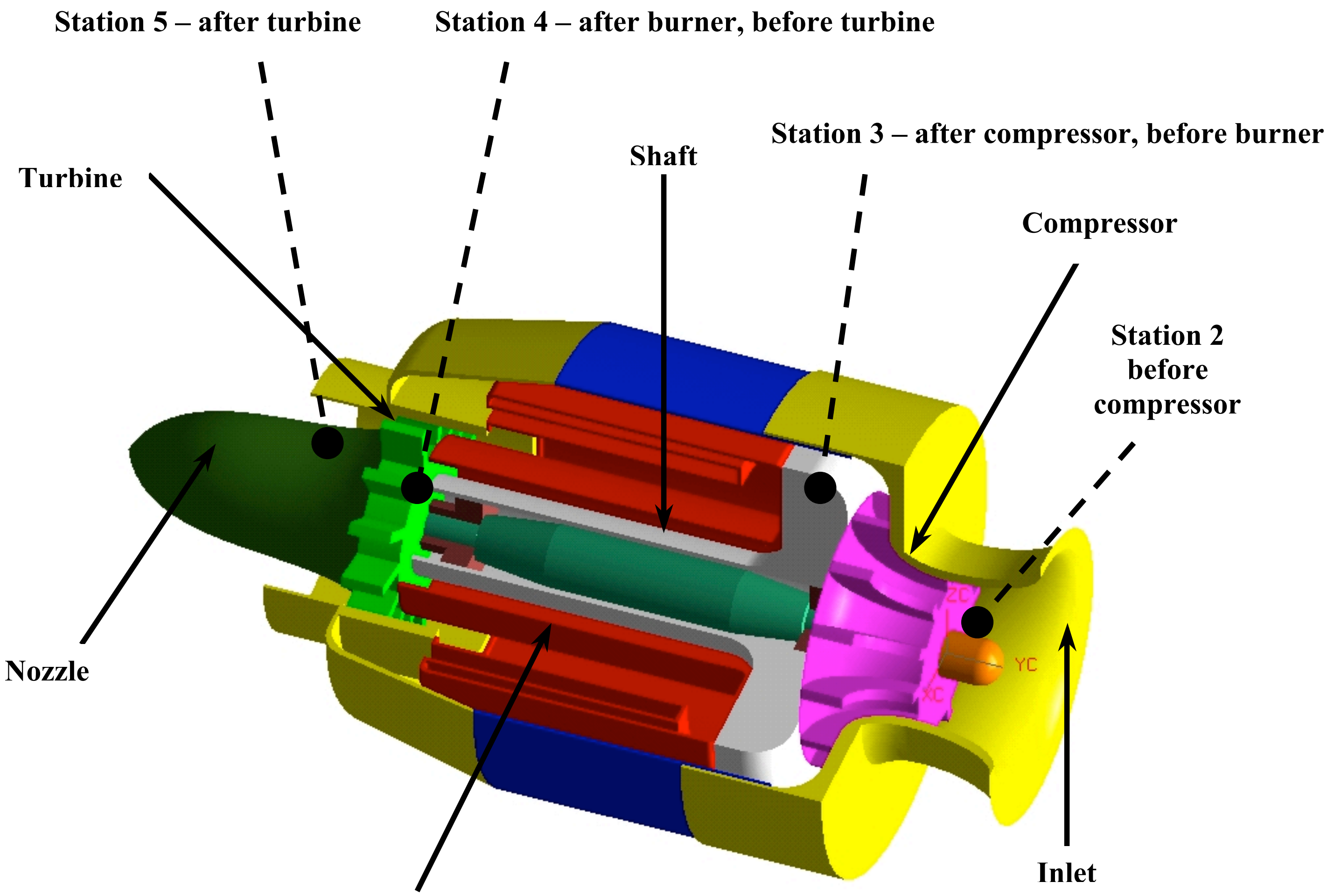


Figure 6 JetStream 66: Detailed Mechanical Layout with Instrumentation Locations

Combustor Can

Experimental Data

Ti= ____ F   Date: Time:

Station number ($_n$)	p_n (psi)	pt_n (psi)	T_n (˚F)
2 = 1			
3			
4			
5			

Fuel (m_f): ____________________ (lbm/s)   Air (m_a): ____________________ (lbm/s)

Experimental Data Analysis/Work Sheet

1. Fuel-to-air ratio: $f = \dfrac{m_f}{m_a}$

$f =$ ____________________

3. Inlet mass flow rate: $m_{o(n)} = s * V_n * A_n$

$s = 1.7$ kg/m^3
V_n= velocity
A_n = area of cross section (πr^2)

Station number (n)	V_n	m_o
2		
3		
4		
5		

4. Exit mass flow rate: $m_{e(n)} = (1+f)m_{o(n)}$

Station number (n)	m_o	m_e
2		
3		
4		
5		

5. Calculated net thrust: $F = m_eV_e - m_oV_o$

F = ____________________

6. Measured net thrust: ____________________

7. Percent Error: $\frac{\text{calculated value} - \text{measured value}}{\text{calculated value}}$ * 100 = ____________%

Acknowledgement

This project was made possible due to the financial of the Ultra Efficient Engine Technology Office of NASA Glenn Research Center. We also acknowledge the efforts of present and past summer interns and explorer post members many of whom has yet to see the final product in operation.